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SYSTEM MATURITY INDICES FOR DECISION SUPPORT IN THE DEFENSE ACQUISITION PROCESS

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System Maturity Indices for Decision Support in the Defense Acquisition Process

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Abstract

The Technology Readiness Level (TRL) scale is a measure of maturity of an individual technology, with a view towards operational use in a system context. A comprehensive set of concerns becomes relevant when this metric is abstracted from an individual technology to a system context, which may involve interplay among multiple technologies that are integrated through the defense acquisition process. This paper proposes the development of a system-focused approach for managing system development and making effective and efficient decisions during the defense acquisition process. For this to be accomplished, a new System Readiness Level (SRL) index will incorporate both the current TRL scale and the concept of an integration readiness level (IRL). This paper describes the foundations for the SRL and provides techniques for determining current and future readiness of a system to determine its position in the defense acquisition process. In addition, it proposes optimization models than can provide management with an optimal development plan that can meet the objectives of the development team, based on constrained resources. These, in turn, can become the foundation for the development of a monitoring and evaluation tool that will be analogous to Earned Value Management used in project management.

1. Introduction

In theory, technology and system development follow similar evolution (or maturation) paths; a technology is inserted into a system (e.g., spiral development) based on its maturity, functionality and environmental readiness, and ability to interoperate with the intended system. However, the assessments made during the acquisition lifecycle that support these decisions are not always effective, efficient, or well developed. Recently, the Government Accounting Office (GAO) stated that many of the programs in the Department of Defense (DoD) plan to hold design reviews or to make a production decision without demonstrating the level of technology maturity that should have been there before the start of development (GAO, 1999). In many US government agencies and contractors, Technology Readiness Level (TRL) is used to assess the maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating a technology into a system or subsystem. In the 1990s the National Aeronautics and Space Administration (NASA) instituted this nine-level metric as a systematic metric/measurement approach to assess the maturity of a particular technology and to allow consistent comparison of maturity between different types of technologies (Mankins, 2002). Given the pragmatic benefits of this concept, in 1999, the DoD embraced a similar TRL concept (USD(AT&L), 2005: DoD, 2005). While the use of TRL is similar in these organizations, TRL was not intended to measure the integration of technologies, but was to be used as ontology for contracting support (Sadin, Povinelli, & Rosen, 1989), thus TRL does not address:

- A complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system (Mankins, 2002; Dowling & Pardoe, 2005; Valerdi & Kohl, 2004),
- The uncertainty that may be expected in moving through the maturation of TRL (Mankins, 2002; Dowling & Pardoe, 2005; Smith, 2005; Cundiff, 2002), and
- Comparative analysis techniques for alternative TRLs (Mankins, 2002; Dowling & Pardoe, 2005; Smith, 2005; Cundiff, 2002).

Based on these fundamental conjectures, a more comprehensive set of concerns becomes relevant when TRL is abstracted from the level of an individual technology to a system context, which usually involves the interplay among multiple technologies. Similarly relevant is the case in which these technologies are integrated through the defense acquisition process. That is, component level considerations relating to integration, interoperability, and sustainment become equally or more important from a systems perspective in an operational environment.

Technology insertion as part of a defense acquisition process needs a quantitative assessment tool that can determine whether a group of separate technology components with their associated (and demonstrated) TRL ratings can be integrated into a larger complex system at a reasonably low risk in order to perform a required function or mission at some performance level.

However, before such a tool can be developed, we must first address the issue of measuring the maturity of the integration elements. The very first attempt to address this was done by Mankins (2002) when he proposed an Integrated Technology Analysis Methodology to estimate an Integrated Technology Index (ITI). The ITI was then used for a comparative ranking of competing advanced systems. The study brought to the forefront the difficulty of progressing through the TRL index and choosing between competing alternative technologies; it did not adequately address the integration aspects of systems development.

Based on concerns for successful insertion of technologies into a system, the Ministry of Defence in the United Kingdom developed a Technology Insertion Metric that includes, among other things an Integration Maturity Level (Dowling & Pardoe, 2005). Building upon these efforts, Gove, Sauser, and Ramirez-Marquez (2008) performed a thorough review of aerospace and defense-related literature to identify the requirements for developing a seven-level integration metric which they called Integration Readiness Level (IRL). It has since evolved into the nine-level concept (Gove, 2007) described in Table 1 below.

Table 1. Integration Readiness Levels

IRL	Definition
9	Integration is **Mission Proven** through successful mission operations.
8	Actual integration is completed and **Mission Qualified** through test and demonstration, in the system environment.
7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.
6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.
5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.
4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.
3	There is **Compatibility** (i.e., common language) between technologies to orderly and efficiently integrate and interact.
2	There is some level of specificity to characterize the I**nteraction** (i.e., ability to influence) between technologies through their interface.

1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.

IRL is a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points. The introduction of IRL to the assessment process not only checks the place of technology on an integration readiness scale, but also presents a direction for improving integration with other technologies. Just as TRL has been used to assess the risk associated with developing technologies, IRL is designed to assess the risk associated with integrating these technologies. Now that both the technologies and integration elements can be assessed and mapped along an objective numerical scale, the next challenge is to develop a metric that can assess the maturity of the entire system that is under development. Sauser, Ramirez-Marquez, Henry, and DiMarzio (2008) were able to demonstrate how using a normalized matrix of pair-wise comparisons of TRLs and IRLs for any system under development can yield a measure of system maturity, called Systems Readiness Level (SRL). The SRL metric can be used to determine the maturity of a system and its status within a developmental lifecycle. Table 2 presents the definitions of the various levels of the SRL and a representation of how the SRL index correlates to a systems engineering lifecycle.

Table 2. System Readiness Levels

SRL	Acquisition Phase	Definitions
0.90 to 1.00	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total lifecycle.
0.70 to 0.89	*Production*	Achieve operational capability that satisfies mission needs.
0.60 to 0.79	*System Development & Demonstration*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40 to 0.59	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
0.10 to 0.39	*Concept Refinement*	Refine initial concept; develop system/technology strategy.

Note: These ranges have been derived conceptually and are undergoing field verification and validation under Naval Postgraduate School Contract # N00244-08-0005.

2. Calculating System Readiness Level

The computation of the SRL is a function of two matrices:

1. Matrix **TRL** provides a blueprint of the state of the system with respect to the readiness of its technologies. That is, **TRL** is defined as a vector with *n* entries for which the i^{th} entry defines the TRL of the i^{th} technology.
2. Matrix **IRL** illustrates how the different technologies are integrated from a system perspective. **IRL** defined as an $n \times n$ matrix for which the element IRL_{ij} represents the maturity of integration between the i^{th} and j^{th} technologies.

In these matrices, the standard TRL and IRL levels corresponding to values from 1 through 9 should be normalized. Also, it has been assumed that on the one hand, a value of 0 for element IRL_{ij} defines that the i^{th} and j^{th} technologies are impossible to integrate. On the other hand, a value of 1 for element IRL_{ij} can be understood as one of the following, with respect to the i^{th} and j^{th} technologies: 1) are completely compatible within the total system, 2) do not interfere with each others functions, 3) require no modification of the individual technologies, and 4) require no integration linkage development. Also, it is important to note that IRL_{ii} may have a value lower than 1, illustrating that the technology may be a composite of different sub-technologies that are not absolutely mature.

In any system, each of the constituent technologies is connected to a minimum of one other technology through a bi-directional integration. How each technology is integrated with other technologies is used to formulate an equation for calculating SRL that is a function of the TRL and IRL values of the technologies and the interactions that form the system. In order to estimate a value of SRL from the TRL and IRL values, we propose a normalized matrix of pair-wise comparison of TRL and IRL indices. That is, for a system with *n* technologies, we first formulate a TRL matrix, labeled [TRL]. This matrix is a single column matrix containing the values of the TRL of each technology in the system. In this respect, [TRL] is defined in Equation 1, where TRL_i is the TRL of technology *i*.

Equation 1.

$$[TRL]_{n\times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \ldots \\ TRL_n \end{bmatrix}$$

Second, an IRL matrix is created as a symmetric square matrix (of size $n \times n$) of all possible integrations between any two technologies in the system. For a system with *n* technologies, [IRL] is defined in Equation 2, where IRL_{ij} is the IRL between technologies *i* and *j*. It is important to note that whenever two technologies are not planned for integration, the IRL value assumed for these specific technologies is the hypothetical integration of a technology *i* to itself; therefore, it is given the maximum level of 9 and is denoted by IRL_i

Equation 2.

$$[IRL]_{n\times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & \ldots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \ldots & IRL_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ IRL_{n1} & IRL_{n2} & \ldots & IRL_{nn} \end{bmatrix}$$

Although the original values for both TRL and IRL can be used, the use of normalized values allows a more accurate comparison when comparing the use of competing technologies. Thus, the values used in [TRL] and [IRL] are normalized (0,1) from the original (1,9) levels.

Based on these two matrices, an SRL matrix is obtained by obtaining the product of the TRL and IRL matrices, as shown in Equation 3.

Equation 3. $$[SRL]_{n\times 1} = [IRL]_{n\times n} \times [TRL]_{n\times 1}$$

The SRL matrix consists of one element for each of the constituent technologies. From an integration perspective, it quantifies the readiness level of a specific technology with respect to every other technology in the system while also accounting for the development state of each technology through TRL. Mathematically, for a system with *n* technologies, [SRL] is as shown in Equation 4.

Equation 4. $$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + IRL_{12}TRL_2 + \dots + IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + IRL_{22}TRL_2 + \dots + IRL_{2n}TRL_n \\ \dots \\ IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \dots + IRL_{nn}TRL_n \end{bmatrix}$$

where $IRL_{ij}=IRL_{ji}$.

Each of the SRL values obtained in Equation 4 would fall within the interval (0,n). For consistency, these values of SRL should be divided by n to obtain the normalized value between (0,1). Notice that [SRL] can be used as a decision-making tool since its elements provide a prioritization guide of the system's technologies and integrations. Thus, [SRL] can point out deficiencies in the maturation process.

The SRL for the complete system is the average of all such normalized SRL values, as shown in Equation 5. Equal weights are given to each technology, and hence, a simple average is estimated. A standard deviation can also be calculated to indicate the variation in the system maturity and parity in subsystem development.

Equation 5. $$SRL = \frac{\left(\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \dots + \frac{SRL_n}{n_n} \right)}{n}$$

where n_i is the number of integrations with technology *i*.

3. An Example of SRL Calculation

The following example will use a real blue-water ship that is currently under development to show the steps involved in calculating its SRL value. This system example will be referred to as *System X* and its contemplated architecture is shown in Figure 1. For this system, the following matrices can be created for the TRL and IRL, based on the definitions presented earlier in Tables 1 and 2.

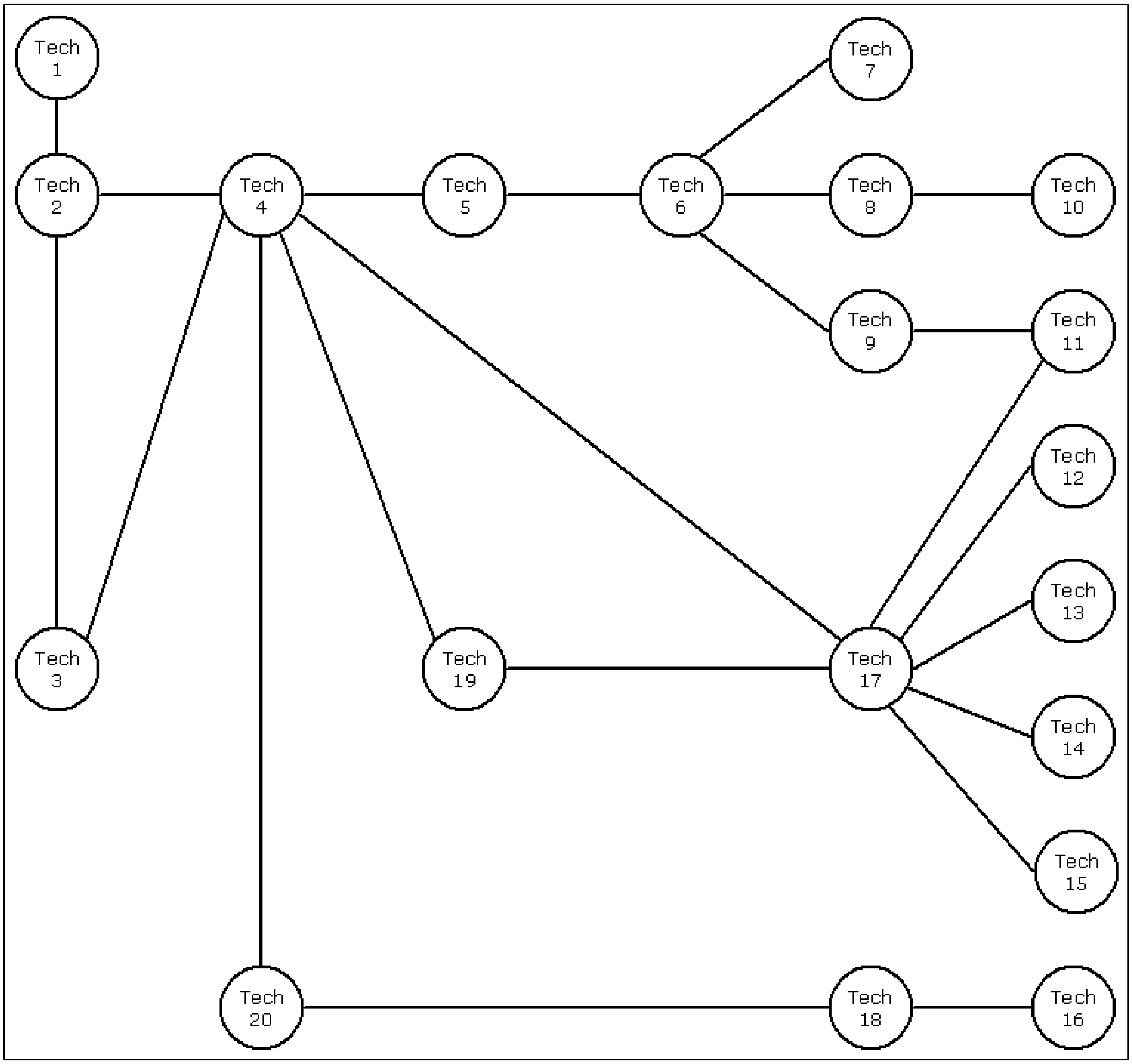

Figure 1. Schematic Architecture of System X

Equation 1a.

$$[TRL]_{20\times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \ldots \\ TRL_{20} \end{bmatrix} = [9 \quad 9 \quad 9 \quad 7 \quad 6 \quad 9 \quad 9 \quad 7 \quad 6 \quad 9 \quad 9 \quad 8 \quad 7 \quad 6 \quad 8 \quad 7 \quad 6 \quad 8 \quad 9 \quad 9]^T$$

Equation 2a.

$$[IRL]_{20\times 20} = \begin{bmatrix} IRL_{11} & IRL_{12} & \dots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \dots & IRL_{2n} \\ \dots & \dots & \dots & \dots \\ IRL_{n1} & IRL_{n2} & \dots & IRL_{nn} \end{bmatrix}$$

$$= \begin{bmatrix}
9 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
9 & 9 & 9 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 9 & 9 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 7 & 9 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 5 & 6 \\
0 & 0 & 0 & 6 & 9 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 7 & 9 & 9 & 8 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 9 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 8 & 0 & 9 & 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 7 & 0 & 0 & 9 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 6 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 8 & 0 & 0 \\
0 & 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 9 & 9 & 9 & 8 & 0 & 9 & 0 & 9 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 & 9 & 0 & 7 \\
0 & 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 9 & 0 \\
0 & 0 & 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7 & 0 & 9
\end{bmatrix}$$

As indicated in the above integration matrix, we assign an IRL value of 0 when there is no integration link contemplated between any 2 technologies. For integration to itself, an IRL value of 9 is used. After normalization of the [TRL] and [IRL] matrices, calculate [SRL] as follows:

Equations 3a and 4a.

$$[SRL] = [IRL]_{20\times 20}[TRL]_{20\times 1} = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_{20} \end{bmatrix}$$

Table 3. Individual SRL Values

SRL_1	SRL_2	SRL_3	SRL_4	SRL_5	SRL_6	SRL_7	SRL_8	SRL_9	SRL_{10}
2.000	3.691	2.605	4.481	1.963	3.728	2.000	2.333	2.000	1.519
SRL_{11}	SRL_{12}	SRL_{13}	SRL_{14}	SRL_{15}	SRL_{16}	SRL_{17}	SRL_{18}	SRL_{19}	SRL_{20}
1.556	1.444	1.333	1.481	1.568	5.778	2.358	2.099	2.210	1.519

Equation 5a.

$$Composite \quad SRL = \frac{\left(\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \dots + \frac{SRL_n}{n_n}\right)}{n} = \frac{\left(\frac{SRL_1}{2} + \frac{SRL_2}{4} + \dots + \frac{SRL_{20}}{3}\right)}{20} = 0.763$$

The calculated Composite SRL index indicates that the system under development is currently in the System Development and Demonstration phase. Aside from providing an assessment of overall system development, it can also be a guide in prioritizing potential areas that require further development. This new index can then interact with decision-making tools for the potential acquisition of systems, which involve the dependency and interplay among performance, availability (reliability, maintainability, and supportability), process efficiency (system operations, maintenance, and logistics support), system lifecycle cost, and system maturity (measured by SRL). The overarching perspective of this methodology provides a context for the “trade space” available to a systems engineer or program manager, along with the articulation of the overall objective of maximizing the operational effectiveness of systems.

4. Potential Applications of SRL: Future Research

Given the ability to estimate readiness of a system under development, organizations can systematically evaluate the implications of using alternative technologies or system architectures, prepare development plans that optimize the objectives of the development team, and eventually be able to evaluate and monitor the progress of the development effort to identify problem areas and corrective measures.

4.1 Optimization Models

In the defense acquisition process, there are factors that may strategically alter the decision to develop one system over another; supersede a new, more functional system over another; determine if a system or technology has become inadequate due to changes in other systems or technologies; invest in the development of a new system or maintain existing systems; and classify a systems obsolescence and longevity. To address these challenges, we can use SRL as a method for determining current and future readiness of a system in order to determine its position in the defense acquisition process. While identifying the current SRL of a system can provide managerial insight, optimizing the future value of this index based on constrained resources will enhance managerial capabilities.

The optimization of SRL based on resource allocation can allow for decisions to be made regarding the trade-offs among: 1) system attributes such as availability, performance, efficiency, and total ownership cost and 2) the components necessary for producing affordable system operational effectiveness (pp. 14-15). These attributes have objectives and ranges for components such as capability, reliability, maintainability, supportability, and producibility, and it is the interplay among them that drives the different levels for both IRL and TRL of the elements in a system. Thus, the optimal selection of which components to enhance to improve the system SRL becomes an optimal system design development problem.

The optimal design of systems is a classical optimization problem in the area of systems engineering. In general, the objective of these problems is to optimize a function-of-merit of the system design (reliability, cost, mean time to failure, supportability, etc.) subject to known constraints on resources (cost, weight, volume, etc.) and/or system performance requirements (reliability, availability, mean time to failure, etc.). To optimize this specific function, it is generally assumed that the system can be decomposed into a system that contains a known number of subsystems or elements (as in Figure 1) and, for each of these elements, a known set of functionally equivalent components types (with different performance specifications) can be used in the design.

From a system engineering design perspective, an optimization approach that balances needs (i.e., the enhancement of the SRL) with resources (i.e., cost of technologies, cost of technology development, etc.), can be an effective and efficient method for reducing risk. That is, the development of a SRL index correlated with the defense acquisition process can be used as an optimization framework for the systems engineer or program manager to design-in enhanced system reliability, maintainability, and supportability to achieve the desired reductions in the necessary logistics footprint and the associated lifecycle cost.

Optimization becomes crucial when trying to decide between competing system design alternatives or when trying to decide which individual TRL or IRL to improve. To make the best decision, optimization models can be developed to assist management to choose SRL improvement opportunities. It is reasonable to assume that improvements will result in costs associated with the purchase of new technology, rework of existing equipment, training of employees, hiring new employees, and enhancements to information technology infrastructure. Two models can be developed. The first model considers minimizing the development cost associated to increasing SRL to some predefined user level, λ. The second model is to maximize the SRL (a function of TRL and IRL) under constraints associated with resources. The mathematical forms of these models follow.

4.1.1 System Cost of Development (SCOD) Minimization

Model $SCOD_{min}$ illustrates an optimization model whose objective is to minimize development cost (a function of TRL and IRL development) under constraints associated with schedule and the required SRL value. The general mathematical form of Model $SCOD_{min}$ follows:

Minimize: SCOD(**TRL,IRL**) = SCODfixed + SCODvariable (**TRL,IRL**)

Subject to: SRL(**TRL,IRL**) ≥ λ

R1 (**TRL,IRL**) ≤ r1

.

.

.

Rh (**TRL,IRL**) ≤ rh

The matrices **IRL** and **TRL** in Model $SCOD_{min}$ contain the decision variables. Each of these variables are integer valued and bounded by (IRL_i,9) and (TRL_i,9), respectively. That is, the TRL/IRL for the i^{th} component cannot be below its current level or above perfect technology development/integration (IRL or TRL = 9).

To completely characterize the decision variables in Model $SCOD_{min}$, it is necessary to introduce the following transformation:

$$y_i^k = \begin{cases} 1 & \text{If } TRL_i = k \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad x_{ij}^k = \begin{cases} 1 & \text{If } IRL_{ij} = k \\ 0 & \text{otherwise} \end{cases} \quad \text{for } k=1,\ldots 9$$

Notice that based on these binary variables, each of the possible TRL and IRL in the system can be obtained as $TRL_i = \sum_{k=1}^{9} ky_i^k$ and $IRL_{ij} = \sum_{k=1}^{9} kx_{ij}^k$. Based on these binary variables, SRL$_i$ is transformed to

$$SRL_i = \left(\sum_{k=1}^{9} kx_{i1}^k\right)\left(\sum_{k=1}^{9} ky_1^k\right) + \left(\sum_{k=1}^{9} kx_{i2}^k\right)\left(\sum_{k=1}^{9} ky_2^k\right) + \ldots + \left(\sum_{k=1}^{9} kx_{ij}^k\right)\left(\sum_{k=1}^{9} ky_j^k\right) + \ldots + \left(\sum_{k=1}^{9} kx_{in}^k\right)\left(\sum_{k=1}^{9} ky_n^k\right)$$

$$\sum_{j=1}^{n}\left(\sum_{k=1}^{9} kx_{ij}^k\right)\left(\sum_{k=1}^{9} ky_j^k\right)$$

Thus, based on the computation of the SRL with these decision variables, Model SCOD$_{min}$ belongs to the class of binary, integer-valued, non-linear problems. For a system with n technologies containing m ($m \le (n-1)n/2$) distinct integrations, and assuming all technologies and integrations are at their lowest levels, there are 9^{n+m} potential solutions to Model SCOD$_{min}$. Evaluating each possible solution is prohibitive, so to generate an optimal solution faster, a meta-heuristic approach developed by Ramirez-Marquez and Rocco (Ramirez-Marquez & Rocco, 2008) will be applied to the system under development. This approach, called Probabilistic Solution Discovery Algorithm (PSDA), has the capability of producing quasi-optimal solutions in a relatively short period of time. However, it must be mentioned that the results cannot be proven to be the optimal solution. Nevertheless, prior tests have indicated that PSDA results tend to be better than results from alternative meta-heuristic approaches.

4.1.2 SRL Maximization

Model SRL$_{max}$ follows the same general formulation. It illustrates the optimization model with the objective to maximize the SRL (a function of TRL and IRL) under constraints associated with resources. This model recognizes that the technologies compete for resources and that benefits can result in an improved SRL via the optimal allocation of such resources. The general mathematical form of Model SRL$_{max}$ is

Model SRL$_{max}$

$$\begin{aligned}
&\text{Max} \quad SRL(\mathbf{TRL}, \mathbf{IRL}) \\
&s.t. \\
&R_1(\mathbf{TRL}, \mathbf{IRL}) \le r_1 \\
&\vdots \\
&R_H(\mathbf{TRL}, \mathbf{IRL}) \le r_H
\end{aligned}$$

The success of implementing these models depends on the consistent and continuous definition of needed capabilities, the maturation of technologies that lead to disciplined development, and the production of systems that provide increasing capability towards a material concept. A fundamental challenge to defense acquisition is that the ultimate functionality cannot be defined at the beginning of the program. Only by the maturation of the technologies, matched with the evolving needs of the user, can they provide the user with capability.

4.2 System Earned Readiness Management (SERM)

The optimization models above can provide valuable insight into the development of a methodology for monitoring and evaluating the overall progress of the development effort. This is primarily due to the fact that the models can identify the optimal development path that can be followed. That is, they identify to what TRL the critical technology elements (CTEs) and which IRL the integration elements should be matured, as well as when those TRLs and IRLs can be achieved.

With these data, we can develop an analytical tool and methodology for evaluating overall progress in systems development as well as measure the impact of alternative or competing architectures, critical technologies and integration elements on the maturity of systems within the systems engineering lifecycle. Furthermore, it can serve as a guide to anticipate the lifecycle implications of the decisions made during the development process. The proposed methodology is termed System Earned Readiness Management (SERM). It will be analogous to Earned Value Management (EVM), an analytical tool used in Project Management (pp. 17-18).

While the optimization models are unavoidably mathematically involved, SERM itself is envisioned to be a relatively simple management tool. It will measure in aggregate terms the level of accomplishment of the system development process. When compared to the development plans and factor estimates that have been prescribed for a particular system under development, management can make conclusions on its status and suggest necessary adjustments to correct any significant deviations. SERM is expected to be valid throughout a wide range of systems with varying degrees of complexity and is intended to be a tool that is easy to use, notwithstanding the complex mathematical algorithms behind it.

Logically, SERM can only be useful if the system under development is already covered by a sufficiently detailed development plan. That is, the system requirements, design and development schedules have already been frozen. However, there are many systems under development that are inherently fraught with high degrees of uncertainty that emanate from the high levels of novelty as well as technology of the system. To be properly managed, such systems have to go through several requirements and design cycles before both can be frozen (Shenhar & Dvir, 2007). However, the need for monitoring and evaluating these systems before the final development cycle still exists. Developing a modified SERM (to be called SERM-U) for such situations will be the ultimate objective.

5. Conclusions

This paper proposes the inclusion of a separate maturity index to measure the progress of the development of the integration links of a system under development. This metric called Integration Readiness Level (IRL) is necessary because in some projects, integration elements have been overlooked and have resulted into major debacles. The paper also introduces the development of a system-focused approach for managing system development and making effective and efficient decisions during the defense acquisition process. For this to be accomplished, a new System Readiness Level (SRL) index will incorporate both the current TRL scale and the proposed IRL metric. The foundations of the SRL are described and we show the techniques for determining current and future readiness of a system to determine its position in the defense acquisition process. In addition, it proposes optimization models than can provide management with an optimal development plan that can meet the objectives of the development team based on constrained resources. These, in turn, can become the foundation

for the development of a monitoring and evaluation tool that will be analogous to Earned Value Management, which is used in project management.

The conceptual development of these metrics and tools outpace their validation and verification in the field. Currently, what is necessary is to have greater involvement from practitioners so that the acquisition community can agree to a common measurement and language that can only improve the system development and acquisition process.

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- MOSA Contracting Implications
- Strategy for Defense Acquisition Research
- Spiral Development
- BCA: Contractor vs. Organic Growth

Contract Management

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- Contractors in 21st Century Combat Zone
- Joint Contingency Contracting
- Navy Contract Writing Guide
- Commodity Sourcing Strategies
- Past Performance in Source Selection
- USMC Contingency Contracting
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- Model for Optimizing Contingency Contracting Planning and Execution

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System Maturity Indices for Decision Support in the Defense Acquisition Process

Brian J. Sauser, Ph.D. and Jose’ E. Ramirez-Marquez, Ph.D.

Stevens Institute of Technology

Abstract

In the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) the Technology Readiness Level (TRL) scale is a measure of maturity of an individual technology, with a view towards operational use in a system context. **A comprehensive set of concerns becomes relevant when this metric is abstracted from an individual technology to a system context, which may involve interplay among multiple technologies that are integrated through a systems engineering process.** This research proposes the development of a system-focused approach for managing system development and making effective and efficient decisions during a systems engineering process. This research will present **a System Readiness Level (SRL) index that incorporates both the current TRL scale and the concept of an Integration Readiness Level (IRL) and provide a method for determining current and future readiness of a system to determine its potential position in the systems engineering process.**

What's Missing in TRL?

- A complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system (Dowling and Pardoe, 2005, Mankins, 2002, Meystel et al., 2003, Smith, 2005, Valerdi and Kohl, 2004),
- The uncertainty that may be expected in moving through the maturation of TRL (Shishko et al., 2003, Cundiff, 2003, Dowling and Pardoe, 2005, Mankins, 2002, Smith, 2005, Moorehouse, 2001), and
- Comparative analysis techniques for alternative TRLs (Cundiff, 2003, Dowling and Pardoe, 2005, Mankins, 2002, Smith, 2005, Valerdi and Kohl, 2004).

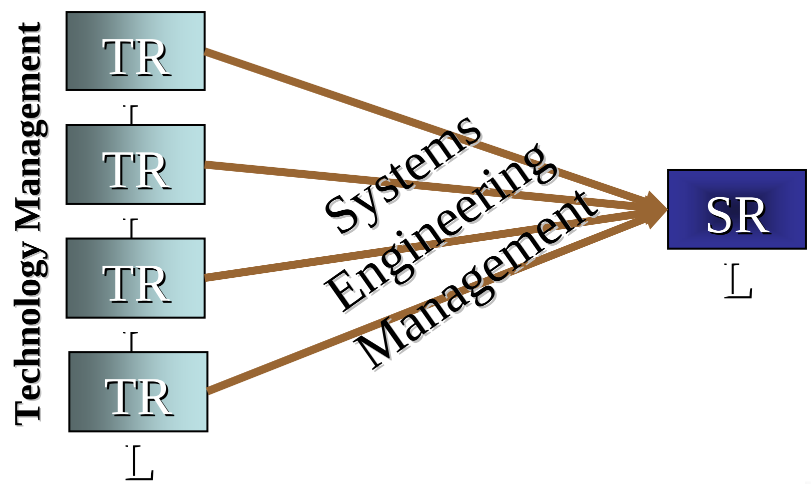
"In order to succeed over the longer term, additional methodologies are needed, including those which allow the identification of anticipated uncertainty in planned R&T programs…" (Mankins, 2002)

Other Work

- Manufacturing Readiness Level (DoD)
  - Used to assess the SE/design process and maturity of a technology's associated manufacturing processes to enable rapid, affordable transition to acquisition programs.
- Integrated Technology Analysis Methodology (ITAM) (Mankins, 2002)
  - Discipline-neutral, quantitative measure of the relative technological challenge inherent in various candidate/competing advanced systems concepts.
- Systems Integration Readiness Level (MoD)
  - System Readiness Levels (*SRL*s) were developed as a tool for projects to assess System Maturity, and to communicate this in a consistent manner.
- Capability RL, Design RL, Habitation RL, Human RL, Logistics RL, Operational RL, and Software RL

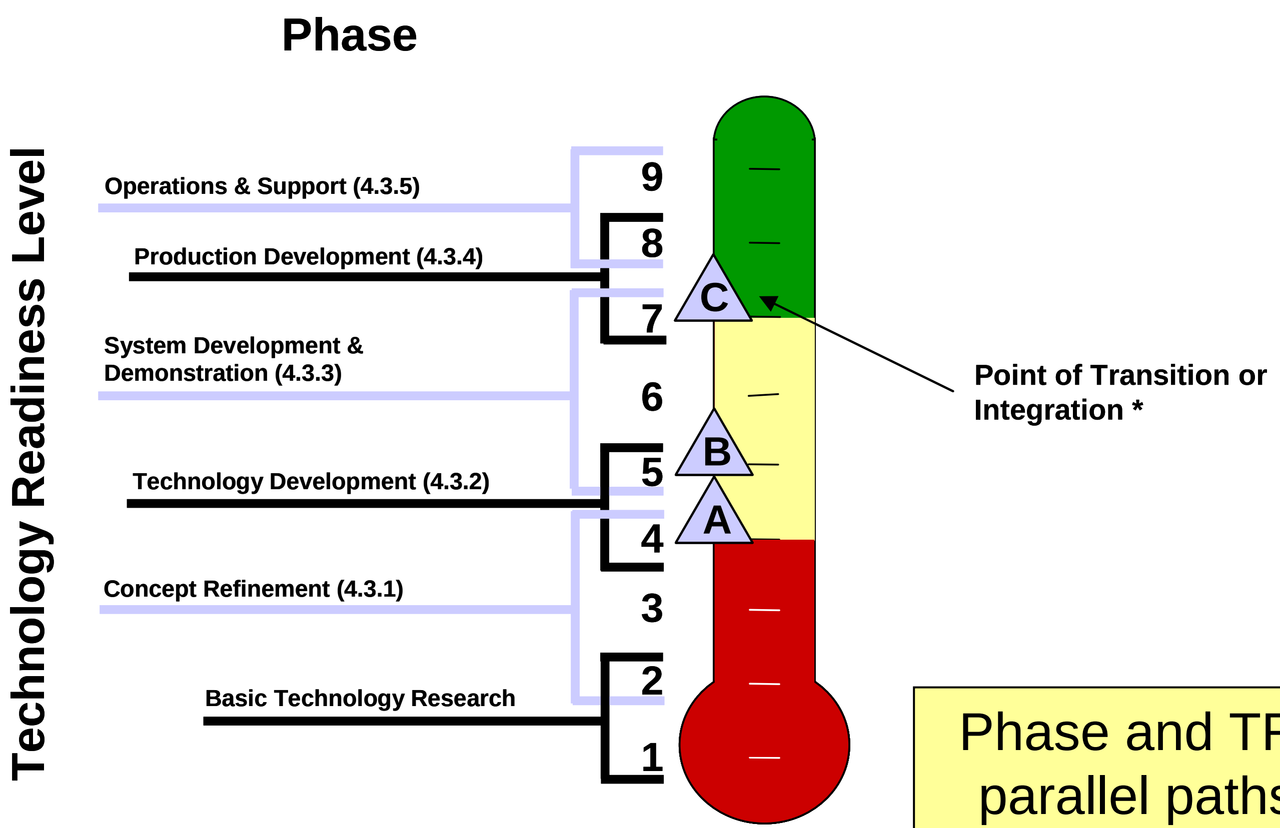
Why do we need a Systems Readiness Level (SRL)?

- TRL is only a measure of an individual technology; it gives no indication of a systems readiness.
- There is no method for integrating TRLs
- There is no systematic measure of a systems readiness.



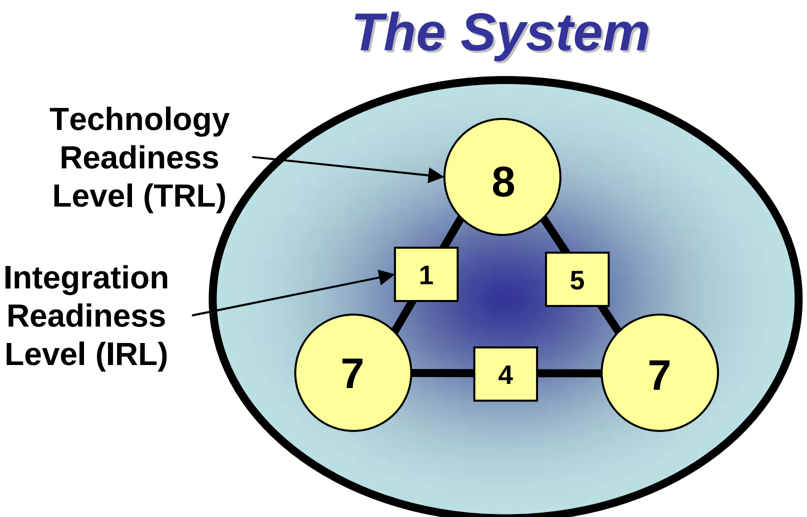
A 1999 GAO Report stated that programs started with a technology at TRL 5 or below experienced "significant cost and schedule increases." GAO also recommended that technologies should mature until the equivalent of TRL 7 before they are included in weapon system programs.

Parallel *(not integrated)* Development



Phase and TRL scales on parallel paths still do not consider integration.

Systems Readiness Level



SRL = *f* (TRL, IRL)

Development of metrics, tool, and methodologies for determining a systems readiness level (SRL) and potential for making efficient and effective life-cycle acquisition and operational decisions. The SRL Model is a function of the individual Technology Readiness Levels (TRL) and their subsequent integration points with other technologies, the Integration Readiness Level (IRL).

- **Value Proposition:**
  - Currently TRL is only a measure of an individual technology
  - There is no method for integrating TRLs
  - There is no systematic measure of a systems readiness
  - Cost and schedule reduction in strategic technology development planning
- **Deliverable:** Integration of methodologies for strategic roadmap planning that illustrate the timely implementation of capability increments.

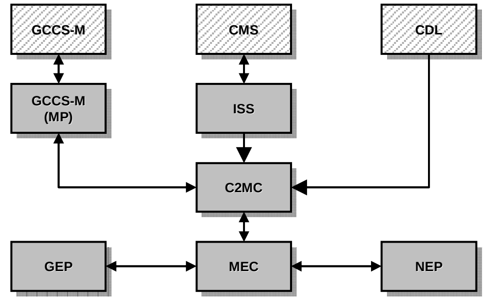
Maturity Indices

LEVEL	TRL Definition	IRL Definition	SRL Definition	SRL VALUE
9	Actual system proven through successful mission operations	Integration is mission proven through successful mission operations	Operations and Support	0.90 to 1.00
			Production	0.80 to 0.89
8	Actual system completed and qualified through test and demonstration	Actual integration completed and mission qualified through test and demonstration in the system environment	System Development and Demonstration	0.60 to 0.79
7	System prototype demonstration in relevant environment	The integration of technologies has been verified and validated with sufficient detail to be actionable		
6	System/subsystem model demonstration in relevant environment	The integrating technologies can accept, translate and structure information for its intended application	Technology Development	0.40 to 0.59
5	Component and/or breadboard validation in relevant environment	There is sufficient control between technologies necessary to establish, manage and terminate the integration		
4	Component and/or breadboard validation in laboratory environment	There is sufficient detail in the quality and assurance of the integration between technologies	Concept Refinement	0.10 to 0.39
3	Analytical & experimental critical function and/or characteristic proof-of-concept	There is compatibility between technologies to orderly and efficiently integrate and interact		
2	Technology concept and/or application formulated	There is some level of specificity to characterize the interaction between technologies through their interface		
1	Basic principles observed and reported	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship		

Step 1: **Identify hardware and software systems to be analyzed**

Include the major technologies and components that make-up the overall system

Step 2: **Define network diagram for systems**



Emphasis is on the proper depiction of hardware and software integration between systems

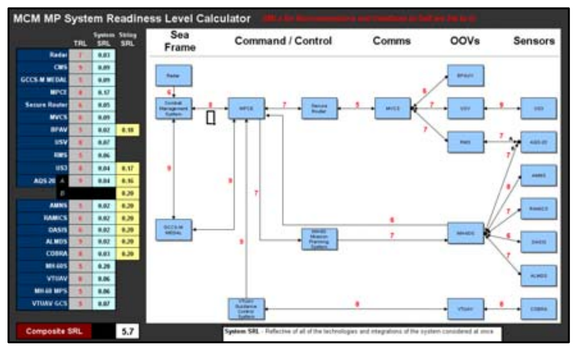
Step 3: **Apply detailed TRL and IRL evaluation criteria to systems**

%	Integration Maturity Level 1
100	Components to be integrated are selected
100	Component interface points are identified
100	Documented phase/build plan for component availability
100	Data types identified

%	Technology Readiness Level 1
100	Physical laws and assumptions used in new technologies defined
50	Have some concept in mind that may be realizable in software
25	Know what software needs to do in general terms
30	Paper studies confirm basic principles and system concepts
N/A	Mathematical formulations of concepts that might be realizable in software
100	Have an idea that captures the basic principles of a possible algorithm
0	Basic scientific principles observed
100	Research hypothesis formulated
75	Identify who will perform research and where it will be done
60	**Readiness Level Percent Complete** (non-weighted)

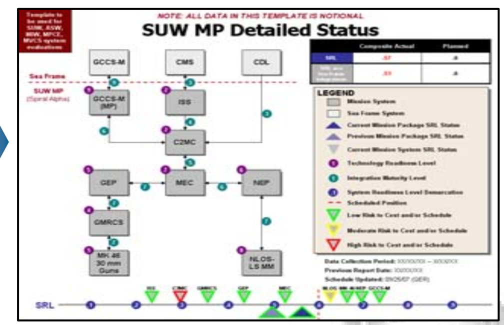
Utilize detailed evaluation criteria to determine the TRL of identified systems and the IRL of defined connections

Step 4: **Calculate individual and composite SRLs**



Leverage TRL and IRL evaluations to compute an assessment of overall system status via SRLs

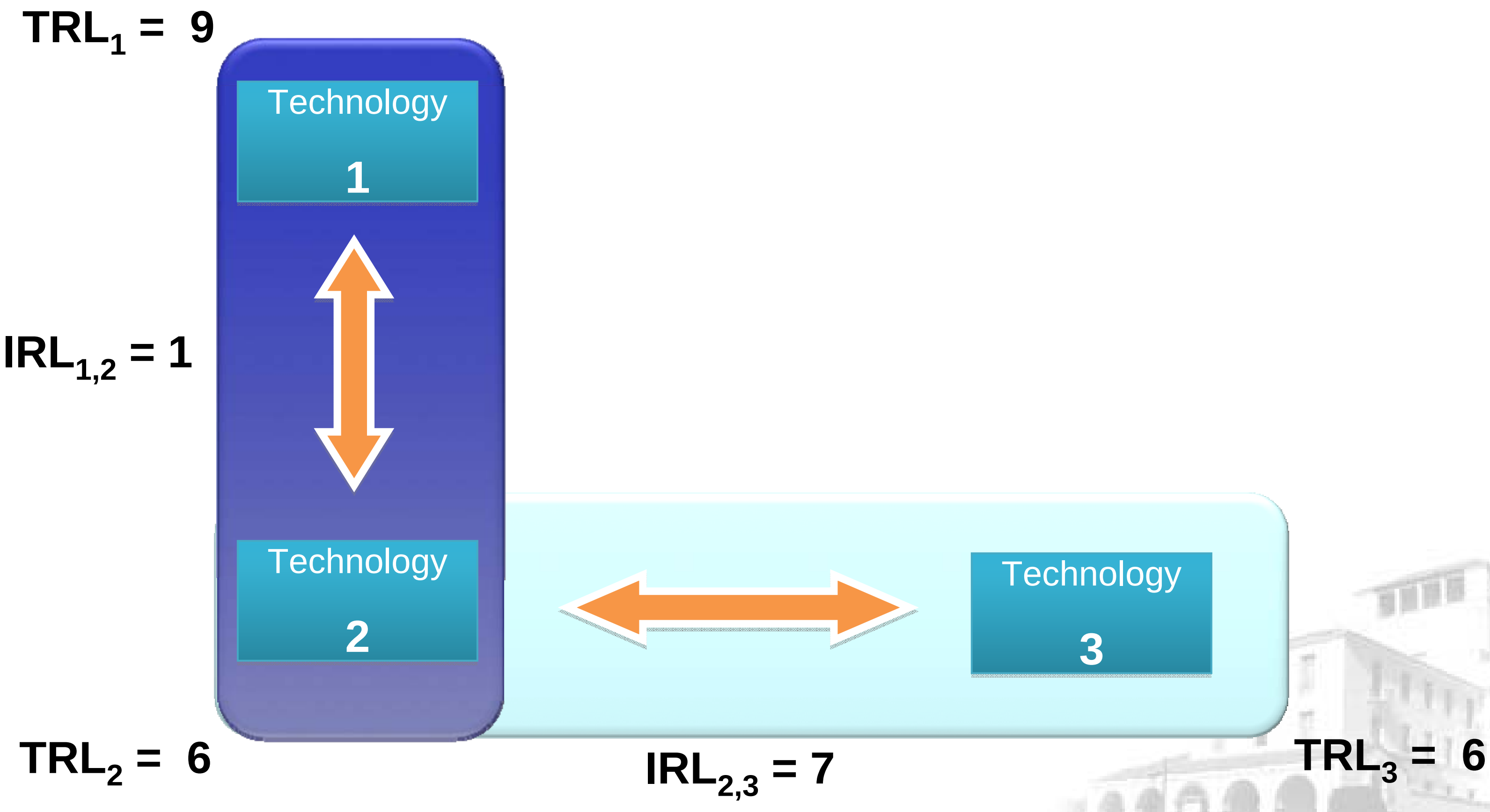
Step 5: **Document status via roll-up charts**



Populate reporting chart templates with evaluation and calculation outcomes to highlight both current status and performance over time

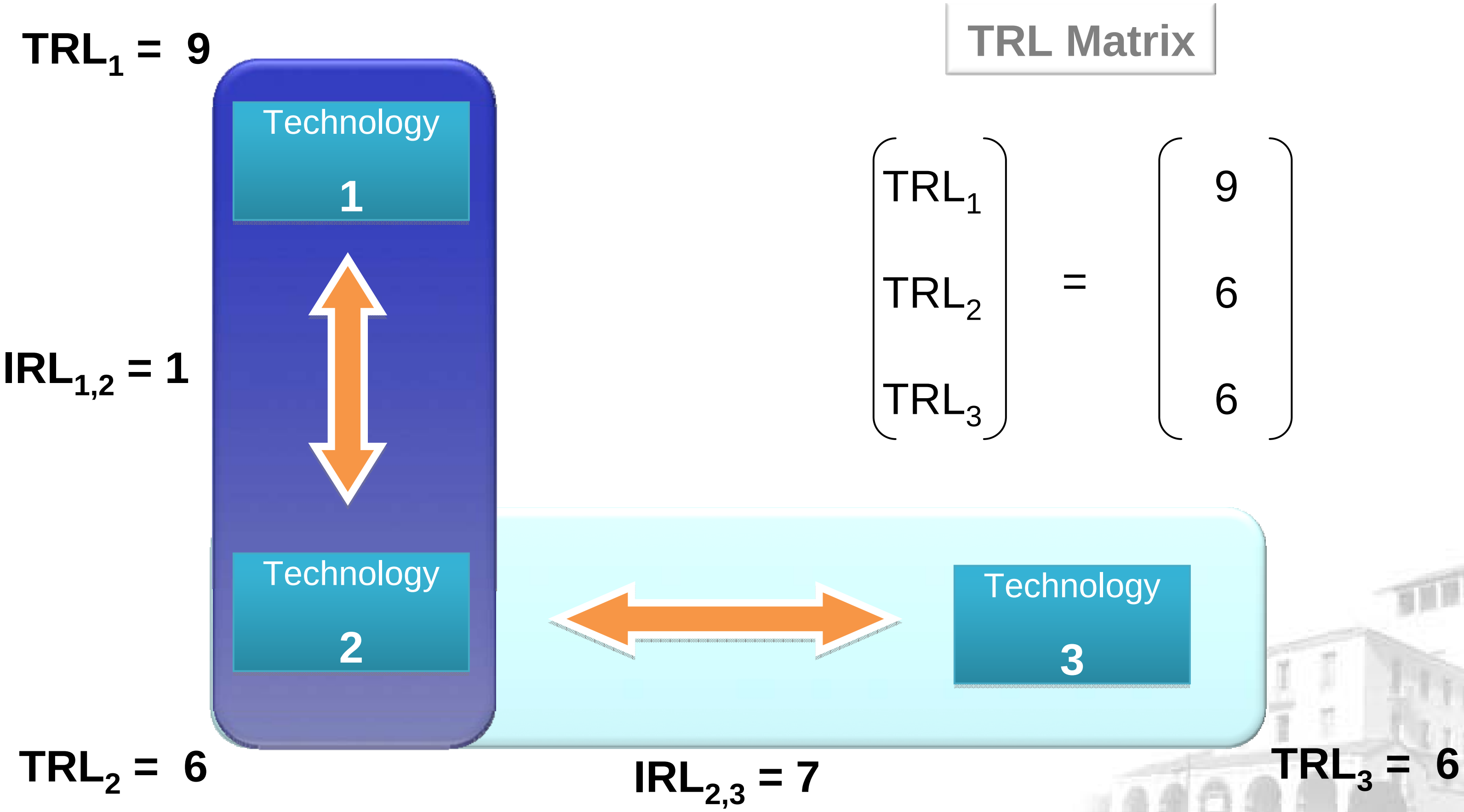
Iterative SME Evaluation Throughout Development Cycle

System Alpha
Determining the TRL and IRL



System Alpha – TRL

Creating the TRL Matrix

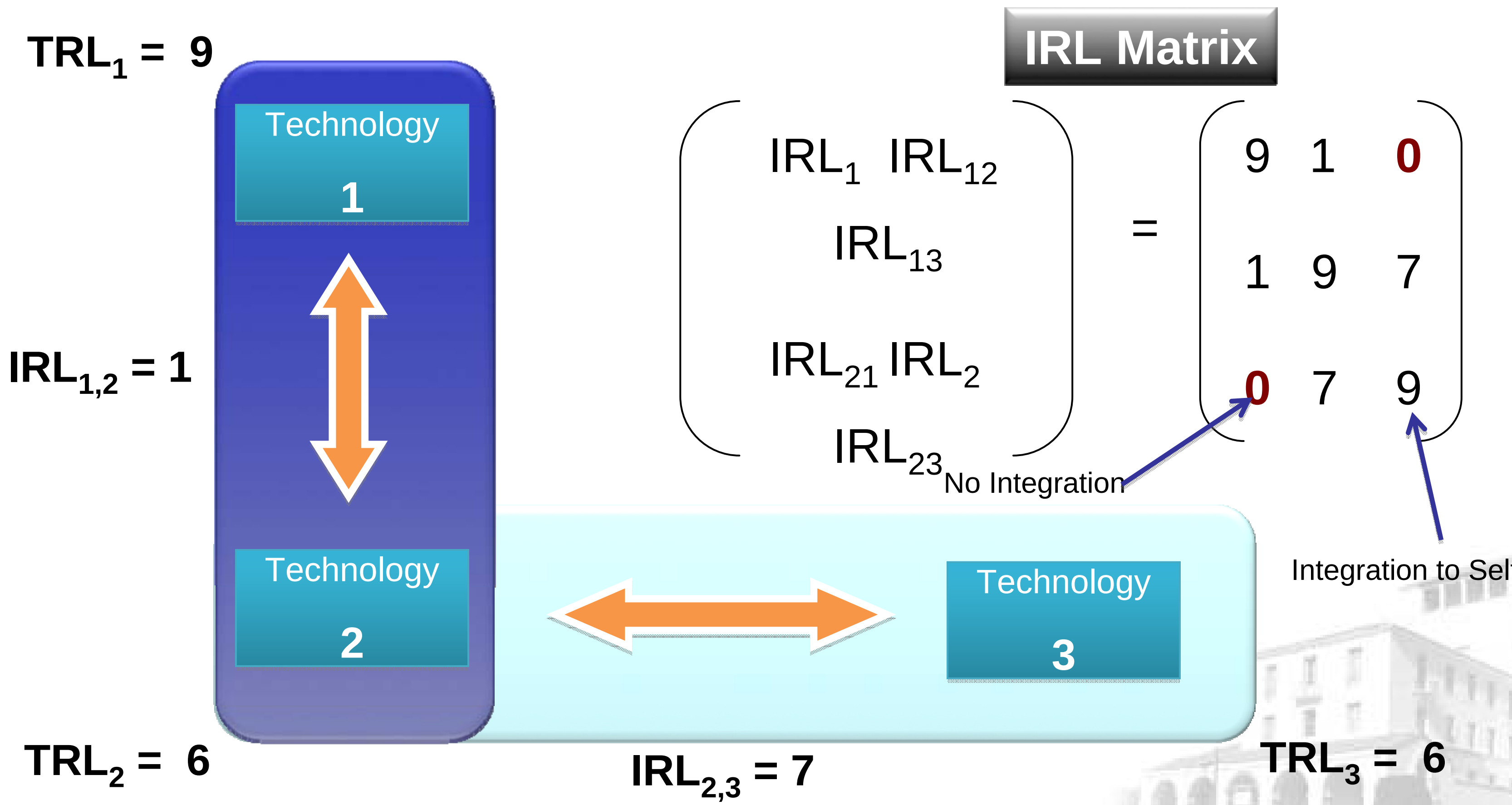


TRL Matrix

$$\begin{pmatrix} TRL_1 \\ TRL_2 \\ TRL_3 \end{pmatrix} = \begin{pmatrix} 9 \\ 6 \\ 6 \end{pmatrix}$$

System Alpha – IRL

Creating the IRL Matrix



SRL for System Alpha

Normalizing the TRLs and IRLs

$$
\begin{pmatrix} IRL_1 & IRL_{12} & IRL_{13} \\ IRL_{21} & IRL_2 & IRL_{23} \\ IRL_{31} & IRL_{32} & IRL_3 \end{pmatrix}
\begin{pmatrix} TRL_1 \\ TRL_2 \\ TRL_3 \end{pmatrix}
\Rightarrow
\begin{pmatrix} 9 & 1 & 0 \\ 1 & 9 & 7 \\ 0 & 7 & 9 \end{pmatrix}
\begin{pmatrix} 9 \\ 6 \\ 6 \end{pmatrix}
$$

Non-Normalized [(0,9) scale]

$$
\begin{pmatrix} 1.0 & 0.11 & 0.0 \\ 0.11 & 1.0 & .78 \\ 0.0 & .78 & 1.0 \end{pmatrix}
\begin{pmatrix} 1.0 \\ 0.67 \\ 0.67 \end{pmatrix}
$$

Normalized [(0,1) scale]

SRL Calculation of System Alpha

Calculating the SRLx

SRL = IRL x TRL

$$
\begin{pmatrix} SRL_1 \\ SRL_2 \\ SRL_3 \end{pmatrix} = \begin{pmatrix} IRL_1 & IRL_{12} & IRL_{13} \\ IRL_{21} & IRL_2 & IRL_{23} \\ IRL_{31} & IRL_{32} & IRL_3 \end{pmatrix} \begin{pmatrix} TRL_1 \\ TRL_2 \\ TRL_3 \end{pmatrix}
$$

$$
\begin{pmatrix} SRL_1 \\ SRL_2 \\ SRL_3 \end{pmatrix} = \begin{pmatrix} 1.07 \\ 1.30 \\ 1.19 \end{pmatrix}
$$

$(0,n_x)$ scale

Note: SRL_x represents Technology X and its IRLs

Sauser, B., J. Ramirez-Marquez, D. Henry and D. DiMarzio. (2007). "A System Maturity Index for the Systems Engineering Life Cycle." *International Journal of Industrial and Systems Engineering*. 3(6). (forthcoming)

SRL for System Alpha

Calculating the Composite SRL

$$\begin{pmatrix} SRL_1 & SRL_2 & SRL_3 \end{pmatrix} = \begin{pmatrix} 1.07 & 1.30 & 1.19 \end{pmatrix}$$

$(0,n_x)$ scale

$$\begin{pmatrix} SRL_1 & SRL_2 & SRL_3 \end{pmatrix} = \begin{pmatrix} 0.54 & 0.43 & 0.60 \end{pmatrix}$$

(0,1) scale

Composite SRL $= 1/3 \; (0.54 + 0.43 + 0.60)$

$= \boxed{0.52}$

Sauser, B., J. Ramirez-Marquez, D. Henry and D. DiMarzio. (2007). "A System Maturity Index for the Systems Engineering Life Cycle." *International Journal of Industrial and Systems Engineering*. 3(6). (forthcoming)

SRL Mapping

0.77 to 1.00	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle.
0.68 to 0.76	*Production*	Achieve operational capability that satisfies mission needs.
0.60 to 0.67	*System Development & Demonstration*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40 to 0.59	*Technology Development*	Reduce technology risks and determine appropriate set
0.10 to 0.39	*Concept Development*	Refine initial concept; Develop system/technology strategy.

SRL3 = 0.60

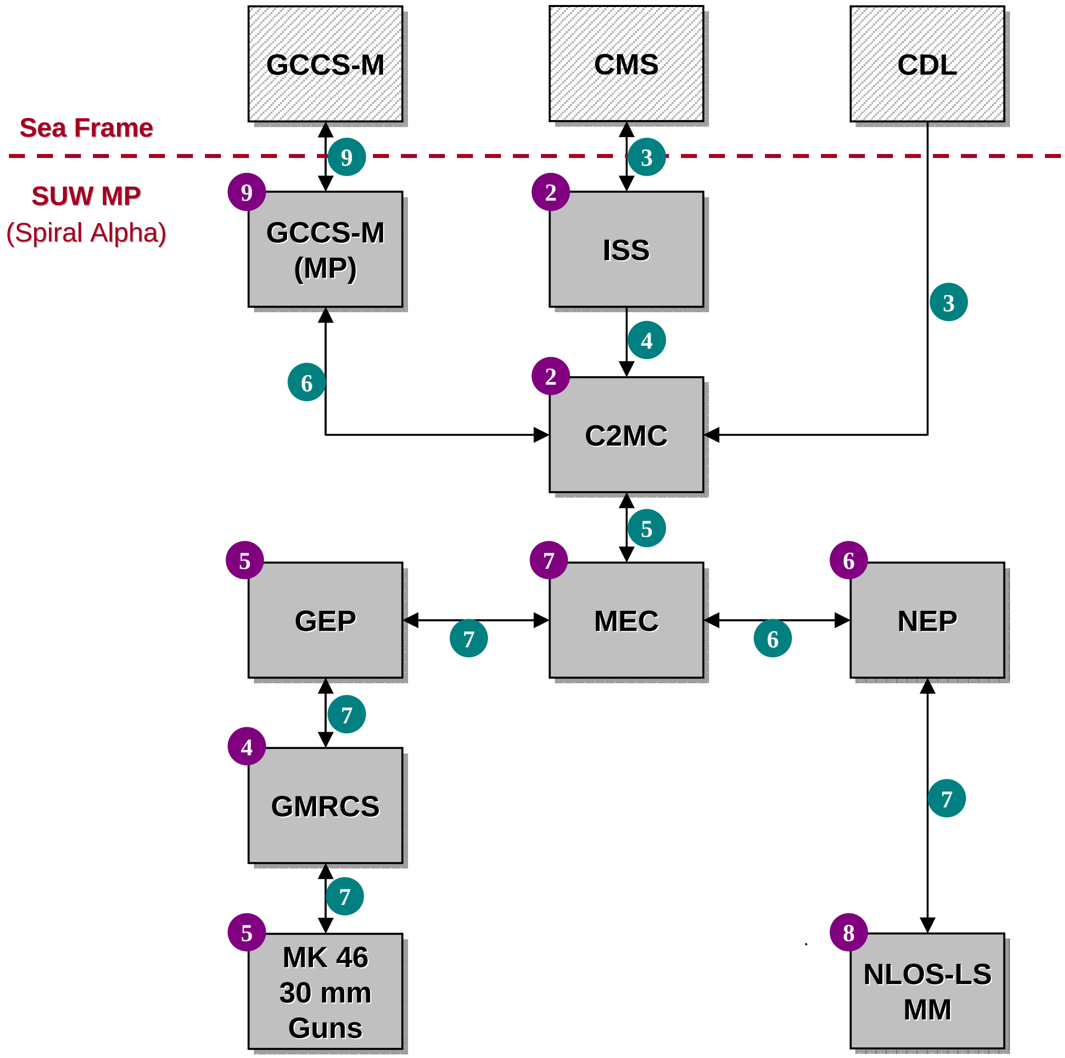
SRL1 = 0.54

SRLcomp = 0.52

SRL2 = 0.43

NOTE: ALL DATA IN THIS TEMPLATE IS NOTIONAL

Detailed Status



	Composite Actual	Planned
SRL	.57	.6
SRL w/o Sea Frame Integrations	.53	.6

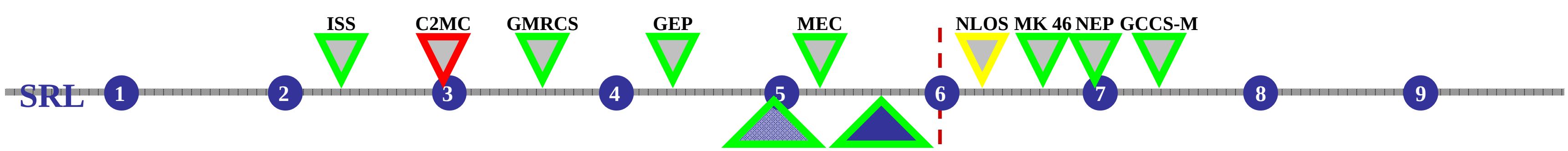
LEGEND

- Mission System
- Sea Frame System
- Current Mission Package SRL Status
- Previous Mission Package SRL Status
- Current Mission System SRL Status
- 1 Technology Readiness Level
- 1 Integration Maturity Level
- .1 System Readiness Level Demarcation
- Scheduled Position
- Low Risk to Cost and/or Schedule
- Moderate Risk to Cost and/or Schedule
- High Risk to Cost and/or Schedule

Data Collection Period: XX/XX/XX – X/XX/XX

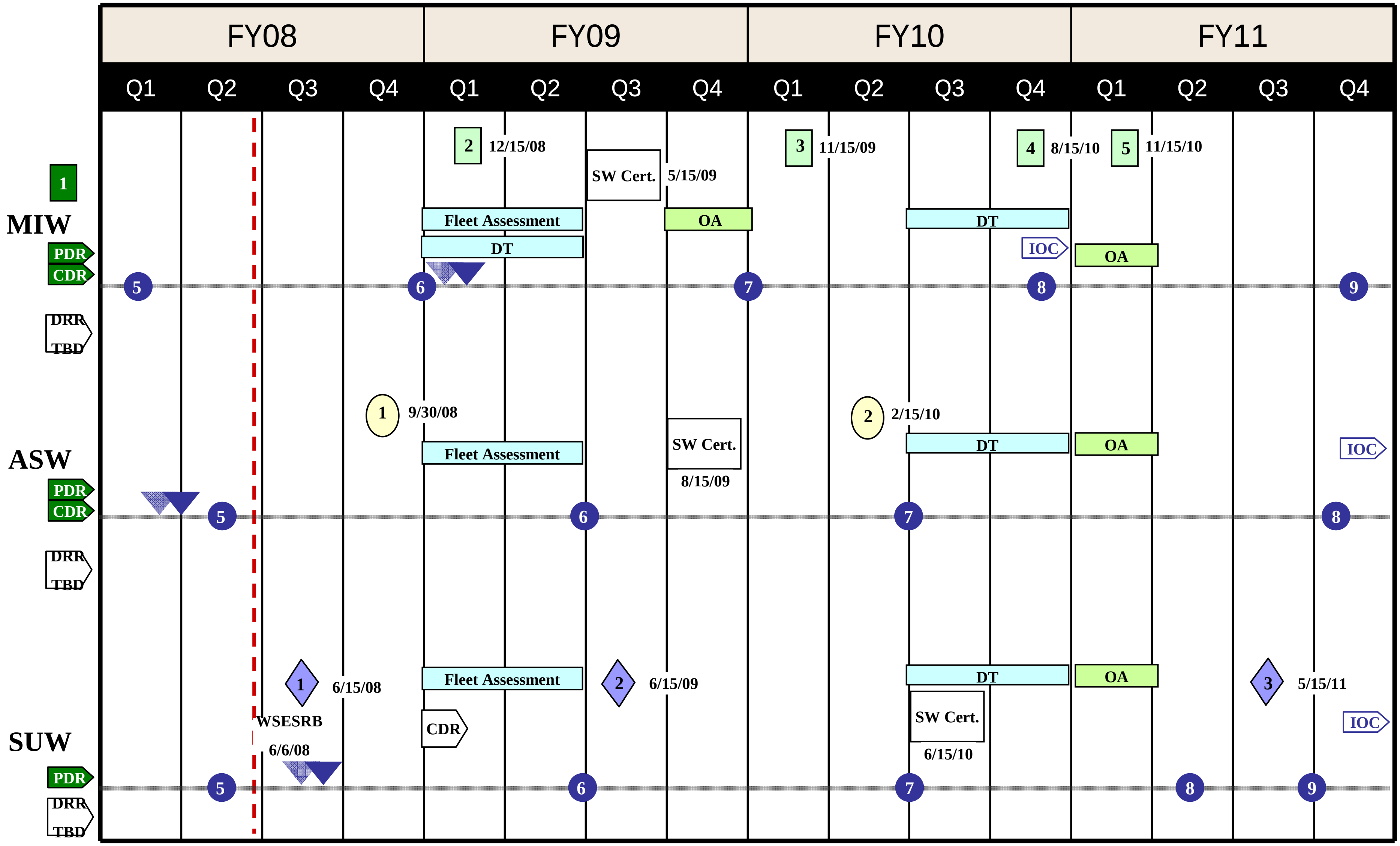
Previous Report Date: XX/XX/XX

Schedule Updated: 09/25/07 (QER)



NOTE: ALL DATA IN THIS TEMPLATE IS NOTIONAL

System Status Roll-up



LEGEND

	Current Reporting Period Status		**Scheduled Position**
	Previous Reporting Period Status	.7	**System Readiness Level**

Data Collection Period: XX/XX/XX – X/XX/XX

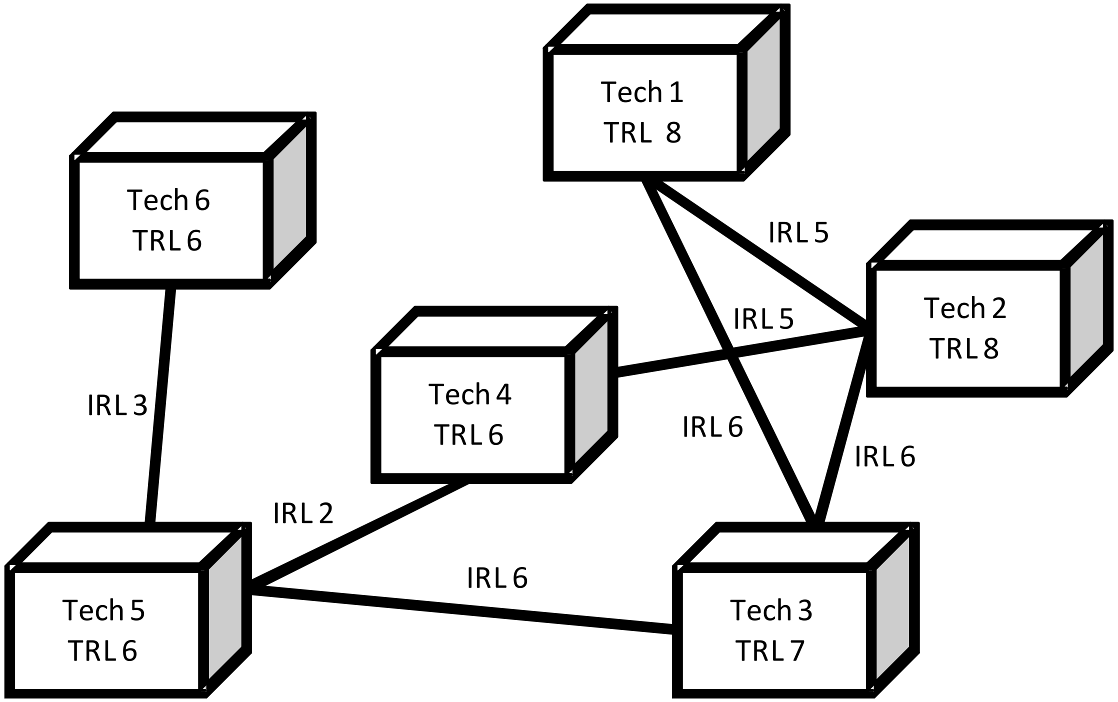
Previous Report Date: XX/XX/XX

Schedule Updated: 09/25/07 (QER)

Current Research

- SRL Resource Optimization
- System Earned Readiness Management (SERM)
- SRL Confidence
- SRL String (“Theory”)

Resource Optimization Models and System Earned Readiness Management (SERM)



ROBOTIC SERVICING MISSION FOR THE HUBBLE SPACE TELESCOPE

Tech 1- Remote Manipulator System (RMS);

Tech 2 - Special Purpose Dexterous Manipulator (SPDM);

Tech 3 - Electronic Control Unit (ECU);

Tech 4 - Autonomous Grappling (AG);

Tech 5 - Autonomous Proximity Operations (APO);

Tech 6 - Laser Image Detection and Radar (LIDAR).

CURRENT SRL = 0.48 (still in Technology Development)

SRL Resource Optimization

Model SRL$_{max}$ = an optimization model with the objective to maximize the SRL (a function of TRL and IRL) under constraints associated with resources.

Case	SRL1	SRL2	SRL3	SRL4	SRL5	SRL6	SRL	COST, $million	TIME, man-hours
100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	26.574	19,122
75%	0.96	0.94	0.96	0.89	0.86	1.00	0.93	19.892	14,044
60%	0.96	0.92	0.94	0.78	0.78	0.89	0.90	15.870	10,254
45%	0.93	0.84	0.89	0.67	0.71	0.83	0.81	11.930	7,283
30%	0.89	0.73	0.84	0.52	0.64	0.78	0.73	7.727	4,961
15%	0.76	0.66	0.76	0.46	0.56	0.67	0.64	3.991	2,733
						Current Status	0.48		

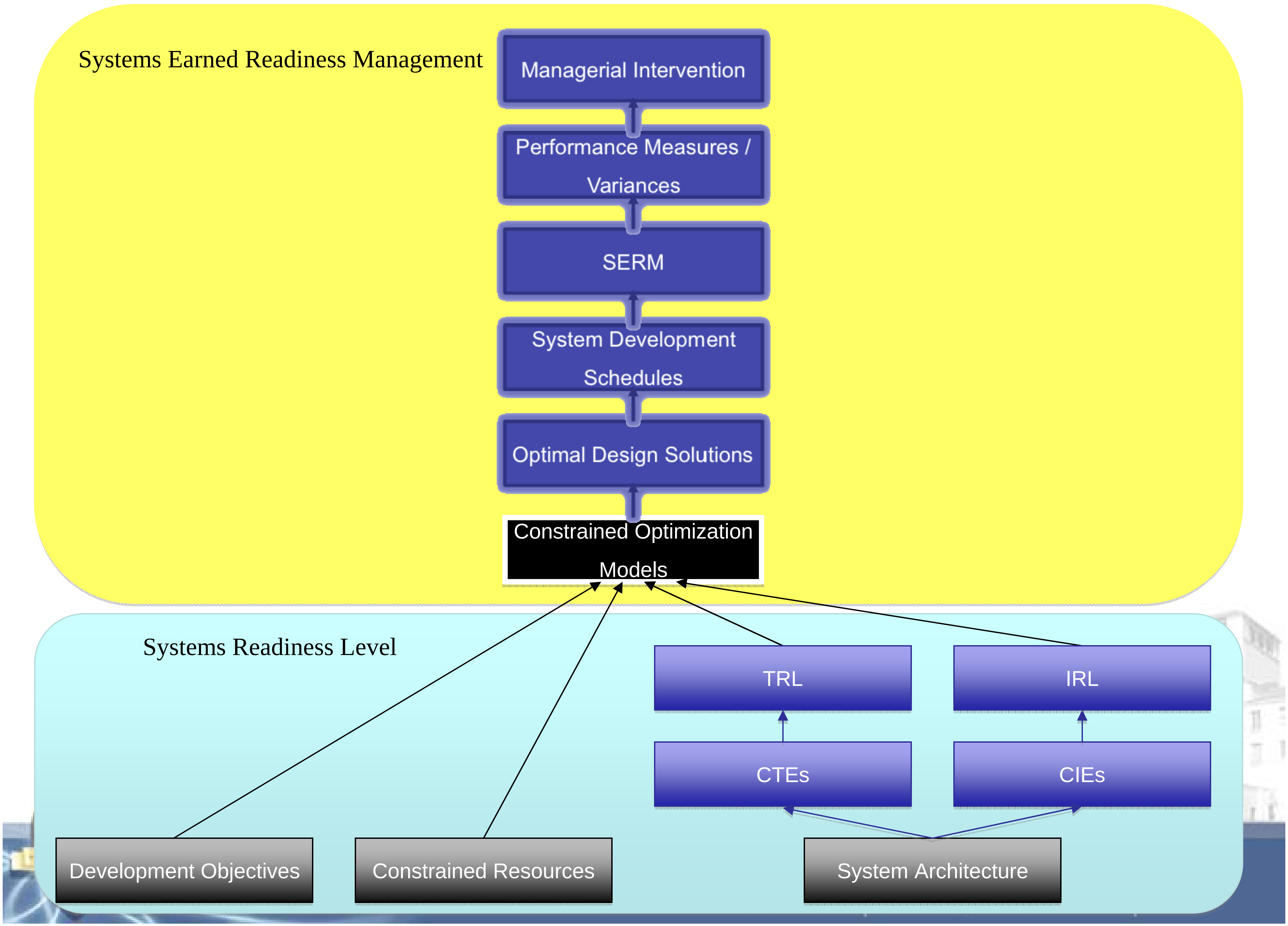
SRL Resource Optimization

Model SCOD$_{min}$ = an optimization model whose objective is to minimize development cost (a function of TRL and IRL development) under constraints associated with schedule and the required SRL value.

Desired Improvements in SRL (%)	SRL		Time (man-hrs)		Computed Minimum Cost ($ x1000)
	Targeted	Computed	Targeted	Computed	
0	0.480	0.480	n.a	n.a	n.a
20	0.584	0.587	3,824	1,654	2,203
40	0.688	0.692	7,649	3,797	5,914
60	0.792	0.794	11,473	7,667	11,065
80	0.896	0.896	15,298	11,309	16,888

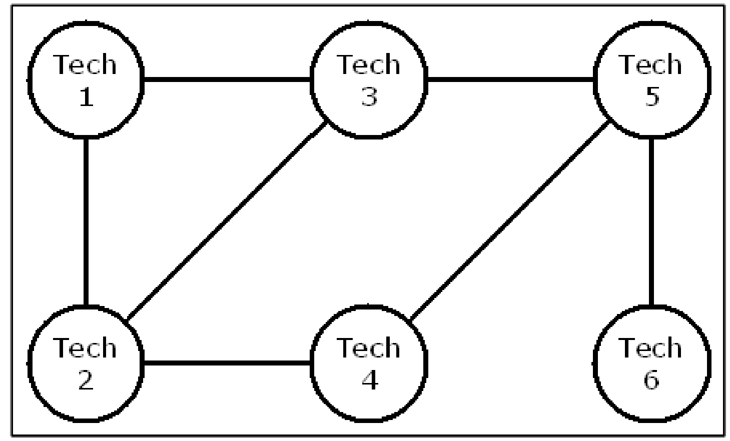
Design Solution from SCODmin Model

Target SRL	TRL						IRL						
	1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
1 (Year 5)	9	9	9	9	9	9	9	9	9	9	9	9	9
0.896 (Year 4)	9	9	9	8	9	9	9	9	9	8	8	5	7
0.792 (Year 3)	8	9	9	6	9	9	9	9	9	5	8	4	6
0.688 (Year 2)	8	8	9	6	9	9	8	8	7	5	7	2	4
0.584 (Year 1)	8	8	8	6	7	6	7	7	7	5	6	2	4
0.48 (Year 0)	8	8	7	6	6	6	5	6	6	5	6	2	2


Systems Earned Readiness Management
Managerial Intervention
Performance Measures / Variances
SERM
System Development Schedules
Optimal Design Solutions
Constrained Optimization Models
Systems Readiness Level
TRL
IRL
CTEs
CIEs
Development Objectives
Constrained Resources
System Architecture

SRL Confidence

SRL Confidence

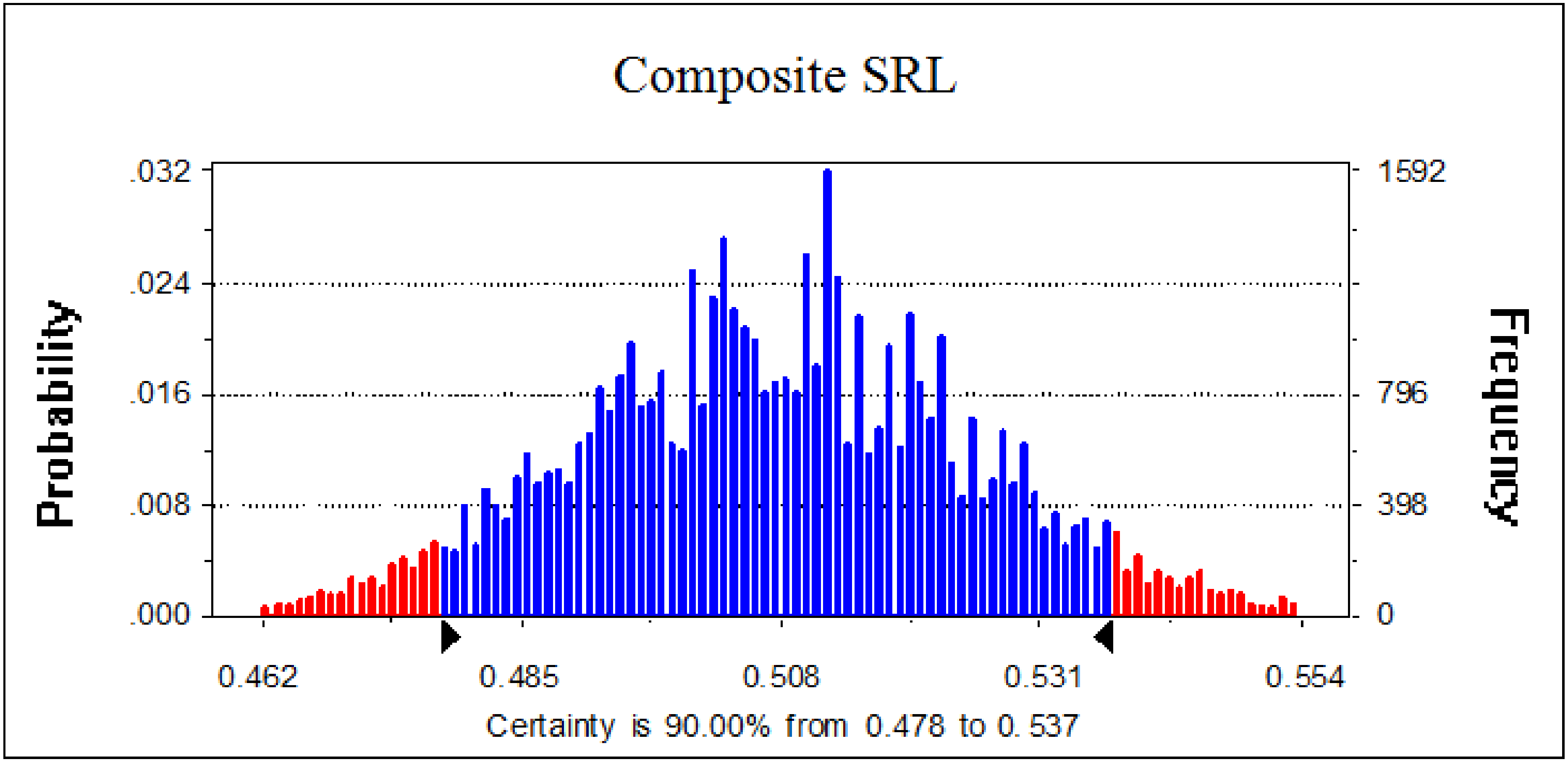


Context Diagram

TRL & IRL States Table

Technology(i)	TRL(k)			Probability ($p_{i0,k}$)			Integration(i,j)	IRL(k)			Probability ($p_{ij,k}$)		
1	7	8	9	0.15	0.80	0.05	1,2	4	5	6	0.05	0.60	0.35
2	7	8	9	0.05	0.80	0.15	1,3	5	6	7	0.20	0.70	0.10
3	6	7	8	0.10	0.80	0.10	2,3	5	6	7	0.05	0.80	0.15
4	5	6	7	0.15	0.80	0.05	2,4	4	5	6	0.10	0.80	0.10
5	5	6	7	0.25	0.70	0.05	3,5	5	6	7	0.20	0.70	0.10
6	5	6	7	0.20	0.70	0.10	4,5	1	2	3	0.15	0.60	0.25
							5,6	2	3		0.40	0.60	

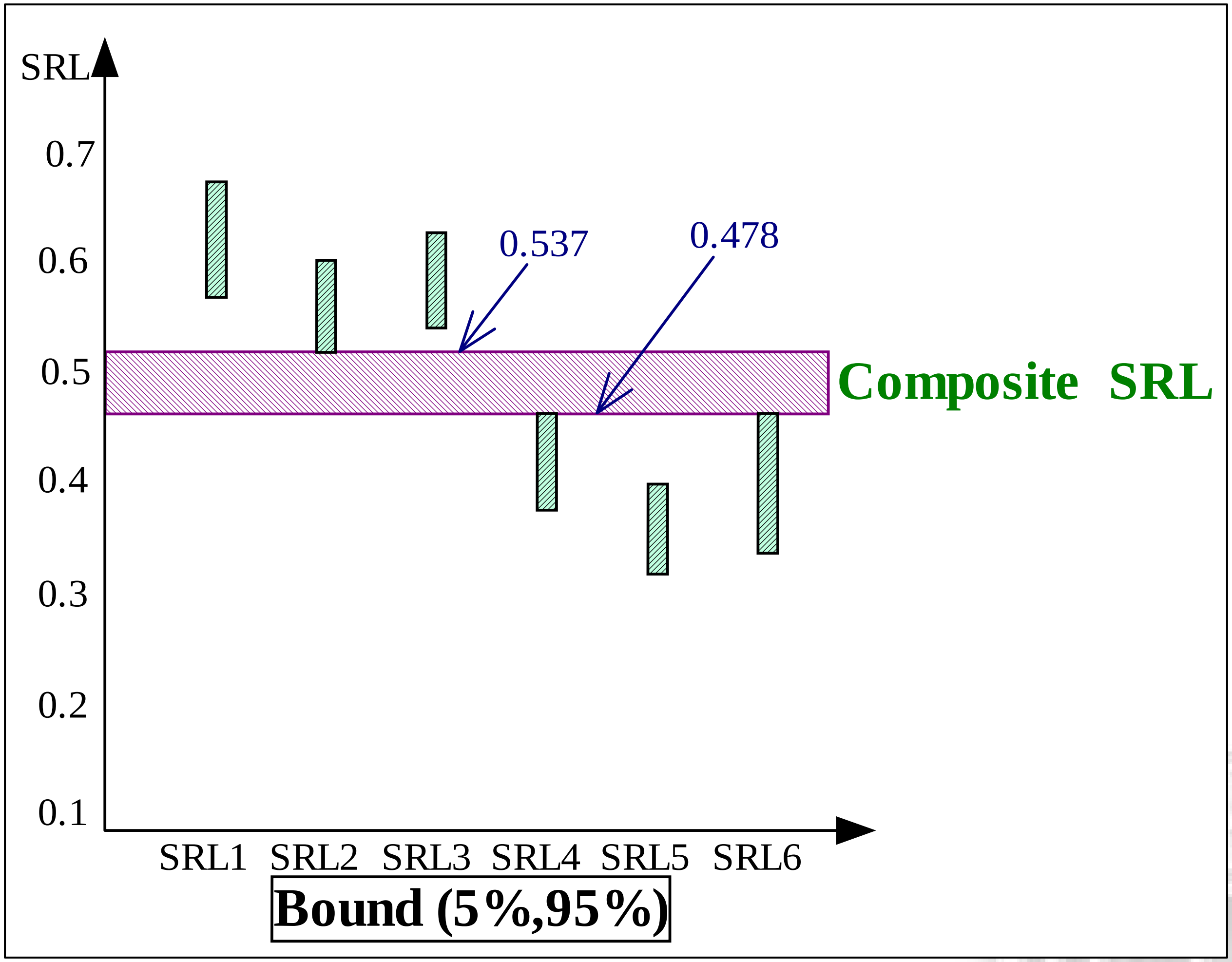
SRL Confidence Simulation



SRL Confidence Simulation Results

Percentile	SRL	SRL1	SRL2	SRL3	SRL4	SRL5	SRL6
0%	**0.435**	0.514	0.448	0.475	0.325	0.278	0.340
5%	**0.478**	0.584	0.534	0.556	0.391	0.333	0.352
25%	**0.495**	0.617	0.562	0.577	0.416	0.358	0.395
50%	**0.507**	0.634	0.574	0.602	0.436	0.370	0.426
75%	**0.519**	0.667	0.593	0.617	0.457	0.389	0.444
95%	**0.537**	0.691	0.620	0.645	0.481	0.417	0.481
100%	**0.587**	0.786	0.682	0.719	0.556	0.488	0.519

SRL Confidence Analysis



SRL String ("Theory")

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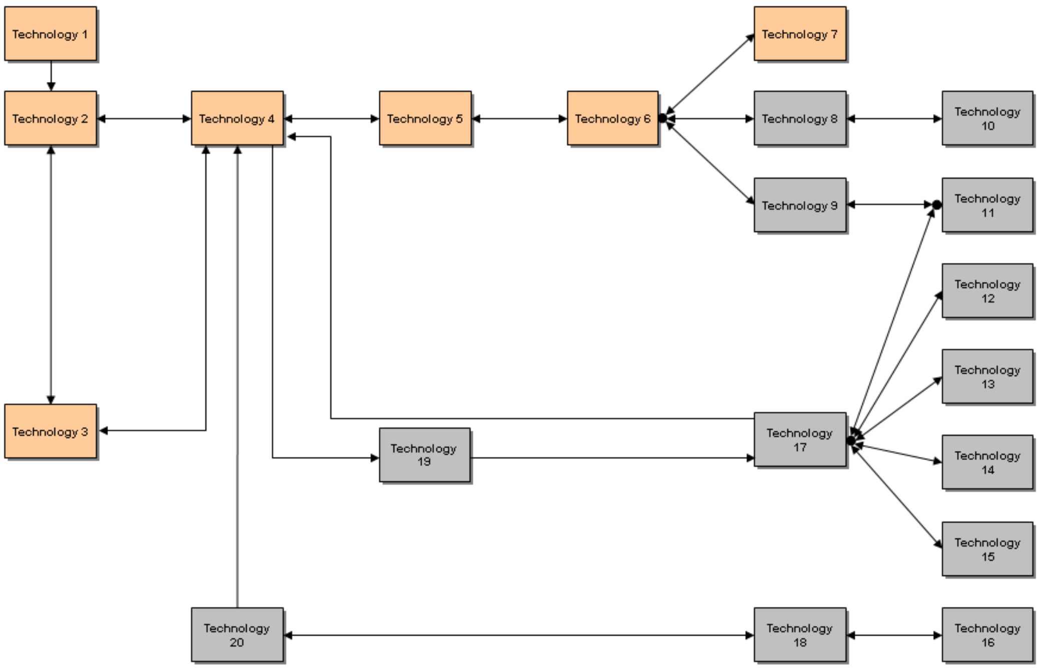
- SRL Evaluations per Mission Thread
- Automatically weights those technologies most important to the system



Future Research Plans

- Case studies for SRL Mapping to Life Cycles
  - New projects. Moving forward
  - Historical data. Failed projects. Completed projects
- SERM Toolset
  - Identify SERM Toolset, i.e: algorithms, applications
  - Evaluate toolset with case studies
- Forecasting and Road mapping
  - Applications for predictive cost and risk forecasting with business case analysis
  - SRL calculator with architecture formation
  - Technology tradeoff environment
  - Disruptive Technologies in Systems Maturity Forecasting
  - Vendor Selection in System Maturity Assessment